

**AFRL-SN-WP-TP-2002-104**

**REDUCED POWER CONSUMPTION IN  
GaAs-BASED BIPOLAR CASCADE  
LASERS**

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**AUGUST 2002**

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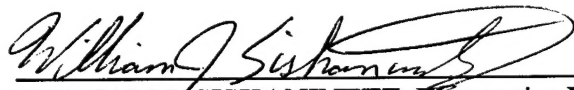
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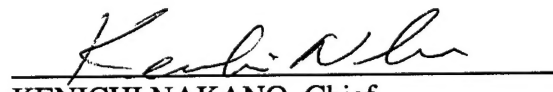
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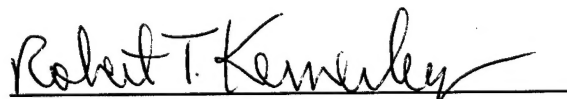
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<b>1. REPORT DATE (DD-MM-YY)</b> August 2002		<b>2. REPORT TYPE</b> Journal Article Preprint		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b> REDUCED POWER CONSUMPTION IN GaAs-BASED BIPOLAR CASCADE LASERS				<b>5a. CONTRACT NUMBER</b> In-house	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b> N/A	
				<b>5d. PROJECT NUMBER</b> N/A	
<b>6. AUTHOR(S)</b> W.J. Siskaninetz, T.N. Dang, and T.R. Nelson, Jr. (AFRL/SNDD) J.E. Ehret and J.E. Van Nostrand (AFRL/MLPS) J.A. Lott (AFIT)				<b>5e. TASK NUMBER</b> N/A	
				<b>5f. WORK UNIT NUMBER</b> N/A	
				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  AFRL-SN-WP-TP-2002-104	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Electron Devices Branch (SNDD) Aerospace Components and Subsystems Division Sensors Directorate Air Force Research Laboratory, Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7318				<b>10. SPONSORING/MONITORING AGENCY ACRONYM(S)</b> AFRL/SNDD	
				<b>11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)</b> AFRL-SN-WP-TP-2002-104	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Sensors Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7318				<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for public release; distribution is unlimited.	
<b>13. SUPPLEMENTARY NOTES</b> This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States. Technical paper preprint submitted on July 29, 2002 for publication in <i>Electronics Letters</i> .					
<b>14. ABSTRACT</b> A systematic study of GaAs tunnel junctions for use in bipolar cascade laser diodes was performed. We investigate the current voltage characteristics of individual degenerately doped n+ and p+ regions grown by MBE and then place the most promising designs within the individual laser substructures. This has resulted in a 1 V reduction in operating voltage, as verified by comparing the lasing characteristics of several edge-emitting laser devices.					
<b>15. SUBJECT TERMS</b> semiconductor devices, lasers, optoelectronics					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT:</b> SAR	<b>18. NUMBER OF PAGES</b> 16	<b>19a. NAME OF RESPONSIBLE PERSON (Monitor)</b> William J. Siskaninetz <b>19b. TELEPHONE NUMBER (Include Area Code)</b> (937) 255-1874 x3515
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			

## Reduced Power Consumption in GaAs-Based Bipolar Cascade Lasers

W. J. Siskaninetz, J. E. Ehret, T. N. Dang, J. E. Van Nostrand, J. A. Lott, and T. R. Nelson, Jr.

A systematic study of GaAs tunnel junctions for use in bipolar cascade laser diodes was performed. We investigate the current voltage characteristics of individual degenerately doped  $n^+$  and  $p^+$  regions grown by MBE and then place the most promising designs within the individual laser substructures. This resulted in a 1 V reduction in operating voltage, as verified by comparing the lasing characteristics of several edge-emitting laser devices.

*Introduction:* Bipolar cascade lasers (BCLs) show excellent potential for producing gain in radio frequency (RF) photonic links[1], improving the efficiency of high-power diode lasers[2], and realizing multiple-color laser devices [3]. High-speed BCLs can be used as the direct-drive optical carrier for an RF photonic link system. The benefits of a BCL over a standard high-speed diode laser include an increased device quantum efficiency, which can be greater than unity, and improved RF impedance matching, since the BCLs can be closely matched to the load impedance by engineering the number of epitaxially grown active region stacks.

A BCL consists of stacked quantum well active regions separated by *reverse-biased* tunnel junctions (TJ). BCLs offer many design tradeoffs, since they can be multiple-cavity or single-cavity devices, and they can be edge- or surface-emitting structures. For a multiple-cavity device each active region exists within its own optical cavity. In a single-cavity device all of the active regions and tunnel junctions are in a single optical cavity. In this article we present the results of our studies on the development of high quality GaAs tunnel junctions grown and incorporated

into multiple-cavity BCLs. We present improved lasing performance in multiple-cavity edge-emitting BCLs with multiple-color emission.

*Tunnel Junctions:* GaAs tunnel junctions are difficult to develop and very little technical detail has been reported in the literature, except from tandem solar cell research [4, 5]. In GaAs-based diodes and BCLs, a major difficulty is achieving high electron concentrations in the  $n$ -doped region. When silicon is used as the  $n$ -dopant, it becomes amphoteric as the doping concentration increases beyond  $5 \times 10^{18} \text{ cm}^{-3}$ . To evaluate tunnel junction performance, several designs were grown in a Varian Gen II MBE system. In all of these structures a 1000 Å GaAs:Si ( $5 \times 10^{18} \text{ cm}^{-3}$ ) buffer layer was grown on an  $n$ -doped GaAs substrate held at 600° C. After the buffer layer was completed the substrate temperature was lowered to 510° C to provide growth conditions for  $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$  quantum wells. The  $n$ -layer of the tunnel junction was formed by growing ten, 10 Å GaAs:Si ( $5 \times 10^{18} \text{ cm}^{-3}$ ) layers separated by nine, 25 second (Si sheet concentration of  $5.5 \times 10^{12} \text{ cm}^{-2}$ ) or 40 second (Si sheet concentration of  $8.8 \times 10^{12} \text{ cm}^{-2}$ ) silicon  $\delta$ -doped "layers," which are simply growth delays while the silicon and arsenic shutters remain open and the gallium shutter is closed. The effective ionized doping concentration,  $n_{\text{eff}}$ , was measured using Hall and electrochemical capacitance-voltage techniques. A 600 Å GaAs:C ( $5 \times 10^{18}$  or  $8 \times 10^{18} \text{ cm}^{-3}$ )  $p$ -layer of the tunnel junction was then grown. Table 1 summarizes the tunnel junction thickness and concentration values used in this study. The tunnel junction devices were processed into squares of varying dimensions with an evaporated Ti:Pt:Au metal contact and annealed at 410° C for 15 seconds. The entire backside was evaporation coated with a standard Ni:Ge:Au:Ni:Au ohmic metal and, again, alloyed at 410° C for 15 seconds.

Figure 1 shows the room-temperature I-V characteristics of four  $200 \times 200 \mu\text{m}^2$  tunnel junction devices. The carbon doping concentration clearly influences the onset of negative differential resistance (NDR) in the tunnel junction device. These results also demonstrate the importance of silicon  $\delta$ -doping parameters on the peak-to-valley characteristics of NDR; silicon  $\delta$ -doping at too high a level results in the silicon becoming an amphoteric dopant. The results from sample TJ #2 clearly demonstrate the desired characteristics of a steep reverse-biased slope and strong evidence of NDR, required for effective BCL operation.

*Bipolar Cascade Lasers:* The BCLs were grown in the same MBE system. The BCL designs consist of two epitaxially stacked lasers: each with  $1 \mu\text{m}$   $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$  digitally alloyed *n*- and *p*-cladding layers, silicon- and carbon-doped respectively to  $4 \times 10^{18} \text{ cm}^{-3}$ ,  $2000 \text{ \AA}$  undoped  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  ternary electrical confinement layers,  $100 \text{ \AA}$  GaAs barriers, and either three  $80 \text{ \AA}$   $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$  quantum wells for emission at  $980 \text{ nm}$  or three  $50 \text{ \AA}$   $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$  quantum wells for emission at  $950 \text{ nm}$ . These lasers were separated by a *reverse-biased* tunnel junction consisting of a  $100 \text{ \AA}$  silicon  $\delta$ -doped layer, described above, and either a  $600 \text{ \AA}$  or  $100 \text{ \AA}$  carbon-doped layer doped at  $5 \times 10^{19} \text{ cm}^{-3}$  or  $8 \times 10^{19} \text{ cm}^{-3}$ . The  $600 \text{ \AA}$  carbon-doped layer was used to replicate the tunnel junction device development and the  $100 \text{ \AA}$  carbon-doped layer thickness was used to evaluate the effect of thickness reduction on laser device properties. The BCLs were fabricated into gain-guided lasers with varying device widths and lengths. Room-temperature pulsed and CW L-I characterization and spectral analysis were performed on all growth structures.

Figure 2 shows a comparison of the L-I and V-I characteristics for the three BCL devices studied and Table 2 provides a summary of the BCL layer characteristics. The stripe geometry was  $20$

$\mu\text{m}$  wide by  $500\ \mu\text{m}$  long for all of the devices. The first room-temperature CW operating BCL (BCL #1) had a tunnel junction with a  $600\ \text{\AA}$  carbon  $p$ -doped layer at  $5 \times 10^{19}\ \text{cm}^{-3}$ . The bottom laser lased first at  $\sim 960\ \text{nm}$  with a threshold current of  $144\ \text{mA}$ . The second laser threshold occurs at  $247\ \text{mA}$  with a lasing wavelength  $\sim 990\ \text{nm}$ . The overall BCL voltage is more than twice the normal operating voltage for a standard InGaAs triple quantum well laser diode indicating additional losses due to the tunnel junction. The next two multiple-cavity, multiple-color BCLs (BCL #2 and BCL #3) were grown to provide a systematic study of the effect of changing the  $p$ -doped layer of the tunnel junction to either a  $600\ \text{\AA}$  or  $100\ \text{\AA}$  C-doped layer doped at  $8 \times 10^{19}\ \text{cm}^{-3}$ . This  $p$ -doping concentration, in both BCL #2 and BCL #3, had the best performing tunnel junction characteristics, as shown in Figure 1. As Figure 2 shows there is a dramatic reduction in operating voltage for both of these devices compared to BCL #1. Increasing the  $p$ -doping concentration significantly improves device operating voltage performance. Reducing the  $p$ -doped thickness of the tunnel junction has little or no effect on the voltage performance with minimal effect on threshold current. The use of this layer is important for making single-cavity BCLs because we desire the smallest possible tunnel junction layer thickness.

*Summary:* We have successfully demonstrated multiple-cavity BCLs. We have significantly improved the device performance by increasing the  $p$ -doping concentration in the tunnel junction from  $5 \times 10^{19}\ \text{cm}^{-3}$  to  $8 \times 10^{19}\ \text{cm}^{-3}$ . Extracting device differential quantum efficiency will require single-color devices. Development of single-cavity single-color BCLs will be required for single-mode operation frequency modulation and relative intensity noise (RIN) experiments.

*Acknowledgements:* The authors would like to thank Joe Breedlove, Paul Cassity, Larry Callahan, and Dan Beasley of Wyle Laboratories for their assistance in the fabrication and technical support in developing these devices. Support is gratefully acknowledged from AFOSR through grant LRIR2305DW and from the Sensors Directorate Entrepreneurial Research Program. W. J. Siskaninetz would also like to thank the Dayton Area Graduate Studies Institute (DAGSI) for their support in his doctoral studies at the Air Force Institute of Technology.

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Table 1: Details of tunnel junction layer parameters. All  $p$ -doped layers are 600 Å, the total  $n$ -layer thickness is 100 Å with ten 10 Å layers doped at  $5 \times 10^{18} \text{ cm}^{-3}$  and 9  $\delta$ -doping interrupts resulting in the following effective  $n$ -doping concentrations,  $n_{eff}$ , as measured using Hall and electro-chemical C-V techniques.

TJ #	$p$ -doping ( $10^{19} \text{ cm}^{-3}$ )	$n_{eff}$ -doping ( $10^{19} \text{ cm}^{-3}$ )	Si $\delta$ -doping (seconds)	Sheet Concentration ( $10^{12} \text{ cm}^{-2}$ )
1	8	0.8	40	8.8
2	8	2.0	25	5.5
3	5	0.8	40	8.8
4	5	2.0	25	5.5

Table 2: Details of bipolar cascade laser parameters. All other layer parameters are the same for each sample grown.

BCL #	$p$ -doping ( $10^{19} \text{ cm}^{-3}$ )	$p$ -thickness ( $\text{\AA}$ )
1	5	600
2	8	600
3	8	100

Figure 1: Room-temperature current versus voltage characterization for 200  $\mu\text{m}$  by 200  $\mu\text{m}$  tunnel junction devices. The dashed line is TJ #1, the solid line is TJ #2, the dotted line is TJ #3, and the dot-dashed line is TJ #4.

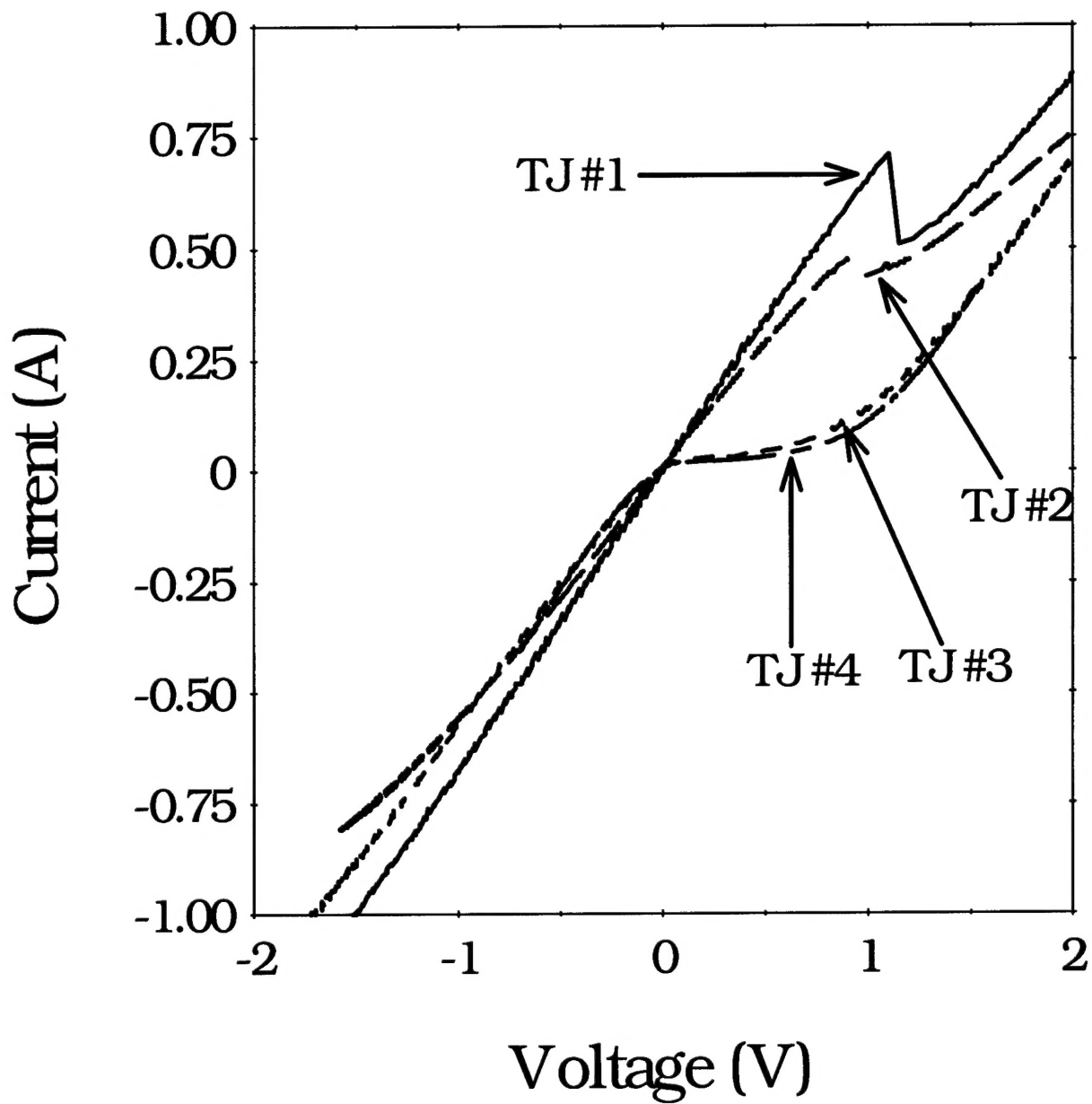


Figure 2: Room-temperature comparison of L-I and V-I operating characteristics for three BCL devices studied. Device dimensions are all  $20\text{ }\mu\text{m}$  wide by  $500\text{ }\mu\text{m}$  long. The solid line is for BCL #1, the dashed line is for BCL #2, and the dotted line is for BCL #3. The inset shows the normalized lasing spectrum at a bias current of 300 mA.

